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The influence of anterior cruciate ligament reconstruction on accelerometric gait analysis

Wpływ przebytej rekonstrukcji więzadła krzyżowego przedniego na akcelerometryczną analizę chodu

Joanna Golec [1 (A,D,E,)], Krzysztof Wójcik [2 (C,E)], Agnieszka Bar [1 (B,C)], Elżbieta Szczygieł [3 (A,F)], Dorota Czechowska [3 (D,F)], Agata Masłoń [3 (D,F)], Iwona M. Tomaszewska [4 (A)]

[1] Department of Rehabilitation in Traumatology, Department of Clinical Rehabilitation, Faculty of Motor Rehabilitation, University School of Physical Education, Krakow, Poland
[2] Production Engineering Institute, Cracow University of Technology, Poland
[3] Department of Rehabilitation in Orthopaedics, Faculty of Motor Rehabilitation, University School of Physical Education, Krakow, Poland
[4] Department of Medical Education, Jagiellonian University Medical College, Krakow, Poland

Key words
trauma disorder, ACL, gait analysis, acceleration, accelerometer

Abstract
Introduction: ACL injuries – next to damage to the collateral ligaments, menisci of the knee – are the most common injuries of the knee joint and very often require surgical treatment. The main aim of the treatment is to restore normal gait pattern. The objective of this study was to determine the influence of reconstructed ACL on selected gait parameters by using an accelerometer system.
Material and methods: The study involved 34 people aged 18-54 who were divided in two groups. The first group consisted of 20 people after ACL reconstruction, aged 19-54 years old (mean 29). The second group consisted of 14 healthy people between the age of 18-45 (mean 25.36). Gait analysis in normal and fast rate was performed using the CQMotion Electronik System, MEMS type.
Results: Differences in the results were observed in the first group. In 75% of people during normal walking and in 95% during fast walking, a 5% difference between the healthy limb and the limb after ACL reconstruction was observed. The gait rate had influence on acceleration value which was observed in RMS (Root Mean Square) values in both of the groups. The RMS value was different, depending on the gait rate.
Conclusions: Accelerometric gait analysis shows that the differences in comparing rate values between limbs are not so great, however, the gait pace has influence on some gait parameters.

Słowa kluczowe
uszkodzenie urazowe, ACL, analiza ruchu, przyspieszenie, akcelerometr

Streszczenie
Wstęp: Uszkodzenia ACL – obok uszkodzeń więzadeł pobocznych, łąkotek stawu kolanowego – należą do jednych z najczęstszych obrażeń stawu kolanowego, wymagających bardzo często rekonstrukcji chirurgicznej. Przywrócenie prawidłowego wzorca chodu staje się głównym celem leczenia. Celem pracy była ocena wpływu przebytej rekonstrukcji więzadła krzyżowego przedniego (ACL) na wybrane parametry chodu w ocenie akcelerometrycznej.
Materiał i metody: W badaniach wzięły udział 34 osoby w wieku 18-54 lat. Do pierwszej grupy włączono 20 osób po przebytej rekonstrukcji ACL w wieku 19-54 lat ($\bar{x}$=29 lat). Do drugiej grupy zakwalifikowano 14 zdrowych osób bez uszkodzeń narządu ruchu w wieku 18-45 lat ($\bar{x}$=25,36 lat). Przeprowadzono analizę chodu we własnym oraz szybkim tempie przy użyciu CQMotion Elektronik System typu MEMS.

The individual authors contributed to this paper in the following way: A – research work project; B – data collection; C – statistical analysis; D – data interpretation; E – manuscript compilation; F – publication search

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Wyniki: W pierwszej grupie, u 75% osób w czasie chodu wolnego, a u 95% podczas chodu szybkiego, wykazano różnicę przekraczającą 5% między kończyną zdrową a poddaną rekonstrukcji ACL. Szybkość chodu miała wpływ na wartość przyspieszenia zaobserwowaną w wartościach RMS w obu grupach. Wartość RMS była różna w zależności o tempa chodu.
Wnioski: Akcelerometryczna analiza chodu pokazała, iż nie odnotowano dużych różnic w porównywanych wartościach przyspieszenia pomiędzy kończynami, natomiast tempo chodu miało wpływ na wybrane parametry chodu.

INTRODUCTION

Traumatic damage to the anterior cruciate ligament (ACL) is a frequent and greatly troublesome knee joint injury related to the working population. Most often, it occurs during the performance of sports activities[1]. Damage to the anterior cruciate ligament, as one of the most frequent types of damage to the knee ligament, can result in functional instability, and in the future - damage to the meniscus and osteoarthritis. In most cases, it requires surgical reconstruction and specialized rehabilitation to restore stability and reduce the risk of further traumatic injury to the joint. A key goal in recovering limb function after surgery is regaining full range of motion, the best possible muscle control, optimal proprioception and proper gait pattern[2,3].

STUDY AIM

The aim of this study was to evaluate the effect of anterior cruciate ligament (ACL) reconstruction on selected parameters of gait using accelerometric assessment.

RESEARCH QUESTIONS

1. During gait, is there a significant difference in the average value of the acceleration measured at the tibial tuberosity of the healthy limb in the forward direction and the average acceleration measured at the tibial tuberosity of the limb after ACL reconstruction?
2. Does gait speed have impact on the change in acceleration value measured at the level of the tibial tuberosity of the lower limbs?
3. Are there differences between the limbs in the average value of RMS (the average resultant vector in the study and control group)?

MATERIAL AND METHODS

The aim of the study was carried out on the basis of the research results, involving 34 participants aged 18-54 ($\bar{x}$ =27.5 years).

The study group consisted of 20 people who underwent ACL reconstruction, including 11 women and 9 men. The age of patients ranged from 19-54 years ($\bar{x}$=29 years). The age of women was between 21-54 years ($\bar{x}$ =33.42 years) and the age of men - in the range of 19-25 years ($\bar{x}$=22.38 years).

The BMI of the subjects in the study group ranged from 20.03-27.47 ($\bar{x}$= 23.20). In women, the index was between 20.03-24.65 ($\bar{x}$ = 22.27) and in males - between 20.45-27.47 ($\bar{x}$= 24.61).

All the participants underwent surgery using the ACL graft tendon or semitendinosus gracilis reconstruction method in the period from 1 to 3 years prior to the ongoing research.

Criteria for inclusion into the study were as follows:
- a history of primary ACL graft tendon or semitendinosus gracilis reconstructive surgery,
- lack of neurological or orthopedic disorders disrupting gait,
- the ability to walk independently without orthopedic aid,
- informed consent to participate in the project.

The control group consisted of 14 healthy subjects, including 7 women and 7 men without musculoskeletal injuries, at a similar age, randomly selected from the population. The age of patients ranged from 18-45 years ($\bar{x}$ =25.36 years). The age of women was in the range of 18-45 years ($\bar{x}$ =24.71 years) and the males - in the range of 22-45 years ($\bar{x}$ =26 years). The BMI of the subjects in the control group was in the range of 16.42-24.91 ($\bar{x}$=21.16). In women, the index was between 16.42-24.65 ($\bar{x}$ =19.70), and in the men - between 20.57-24.91 ($\bar{x}$=22.61).

All participants included in the project agreed to participate in the study. The test method was consistent with the principles of the Declaration of Helsinki.

The study was carried out using the funds from project No. 66/BS/KRK/2015.

The study was conducted using the CQMotion Elektronic System, MEMS type computerized gait analyzer with inertial sensors (equipment produced at CQ Elektronic System, Poland). The analyzer comprises of sensors with a built-in accelerometer, magnetometer and gyroscope. They record data on three mutually perpendicular axes - X, Y, Z. The test consisted of placing the accelerometer sensors on selected anthropometric points of the subject's body. The obtained data were transferred to a computer where the results were converted and subjected to mathematical and later statistical analysis.

For the purpose of this study, two sensors were placed on the tibial tubercle of the left and right limb. The accelerometer was used to measure the acceleration of the material point in units of m/s^2.

The subjects covered the 8-m distance on a flat surface four times. The first walk covering the 8-m distance, there and back, was done at the subject's preferred walking pace, the second, however, was quick paced.

In order to minimize measurement errors, the sensors were applied to all of the study participants by the same person. The data were saved to text files as numerical sequences (time, acceleration). An example of the function course is shown in Figure 1.

In Figure 1, three courses of acceleration in time are shown. The colours indicate the directions, respectively:
- red – up-down, vertical axis Y,
- black – front-back, sagittal axis Z,

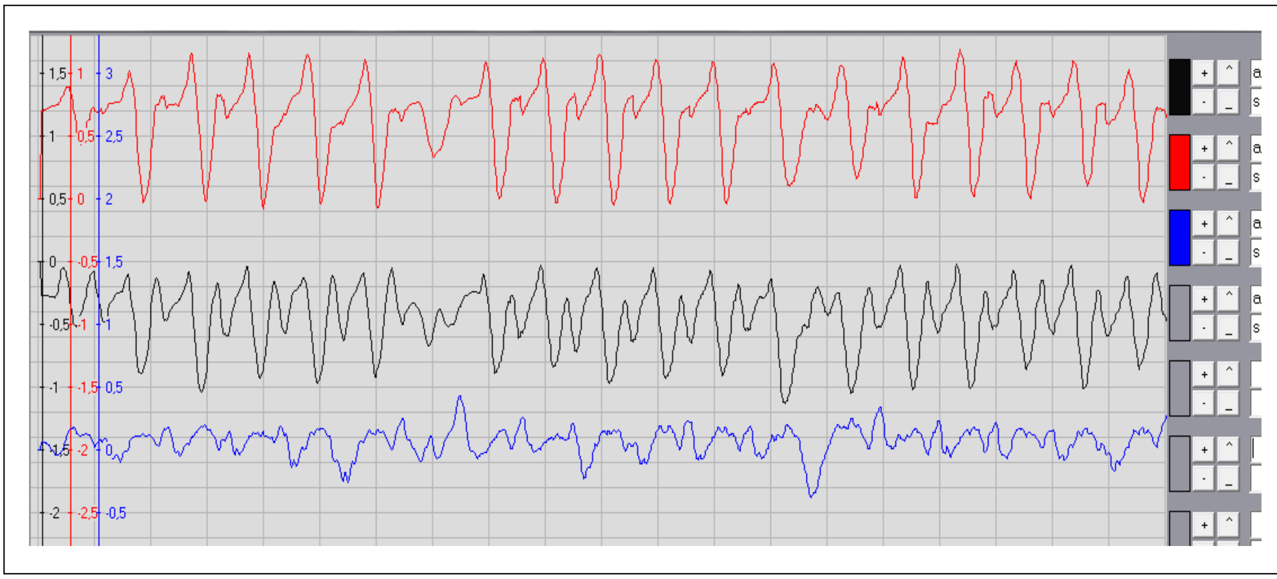

Figure 1

Proper course of accelerations (own source)

– blue – left-right, transverse axis X.

These signals were subjected to computer analysis aimed at detecting differences in the shapes of the function course for the left and right limb. Due to the fact that the acceleration in the up-down direction (Y-axis) includes a dominant component, which is derived from the acceleration of gravity, the difference in acceleration between the left and right limb are difficult to analyze and are not considered in this study (taking the value of gravity acceleration into account requires precise knowledge of its direction). The Y signal is only used to distinguish the signals of individual steps. Heel strike on the ground during the phase of Initial Contact is characteristic for initiation of the Stance phase. It allows automatic separation of steps and, consequently - determination of the time intervals in which the signal is analyzed.

In the research, we considered the a_z acceleration signal in the front-back direction (Z-axis sagittal) as well as a_x in the lateral direction (transverse axis X), and the signal representing the sum of the above two accelerations:

$$a_w = \sqrt{a_x^2 + a_z^2}$$

This acceleration is called resultant or total (for reasons earlier described, it does not take the vertical component into account).

For each of the discrete times *t*, the three values (a_x, a_z, a_w) were therefore obtained, separately for each limb of the tested person. For each of the above six signals, RMS (Root Mean Square) values were calculated within the studied time intervals.

STATISTICAL HYPOTHESIS

There is a difference in the average RMS acceleration value of the tibial tuberosity between the healthy limb and the limb subjected to ACL reconstruction.

Due to the fact that in the work we compared samples for the two limbs (left and right), the suitable statistical method checking the above hypothesis is the test for significance of differences between two means. The study used the Student's t-test[4]. It determines the likelihood of the so-called type I error, i.e. the probability of rejecting the hypothesis that the observed samples come from distributions with identical mean values, in favour of the hypothesis stating that the distributions have different means. In our case, it is the average RMS values for the left and right limbs. Therefore, formally, we are examining the hypothesis opposite to that described above.

In the study, we assumed the maximum value of the type I error (confidence level) equal to 0.05.

Calculations were conducted using a spreadsheet.

RESULTS

For patients enrolled in the study and control group, we analyzed readings from accelerometers placed on the tuberosity of the tibia of both lower limbs.

1. The differences were evaluated in RMS values for total acceleration a_w during brisk walking and at one's own pace in the control group (Table 1 and 2).
2. The differences were evaluated in the course of RMS accelerations during brisk walking and at one's own pace in the study group, individuals subjected to ACL reconstruction (Table 3 and 4).

The Student's t-test for the significance of differences between mean values was performed.

The analyzed values were the mean square values of RMS acceleration measured in two directions (X-side, Z-front), separately for the left and right limb and RMS of the resultant acceleration.

The research was conducted in two independent trials - for the study and control group. The tests were carried out for two different walking speeds

Table 1

RMS for control group (healthy individuals) – brisk walking

Person	Left limb			Right limb		
	side	front	total	side	front	total
1	0.114	0.592	0.706	0.194	0.521	0.715
2	0.257	0.552	0.809	0.190	0.495	0.685
3	0.268	0.400	0.668	0.120	0.450	0.570
4	0.083	0.763	0.846	0.083	0.656	0.739
5	0.111	0.593	0.704	0.127	0.738	0.865
6	0.104	0.982	1.086	0.298	0.958	1.256
7	0.264	0.783	1.047	0.115	0.778	0.893
8	0.096	0.918	1.013	0.345	0.837	1.182
9	0.159	1.069	1.228	0.244	0.851	1.095
10	0.163	0.493	0.656	0.544	0.305	0.848
11	0.064	0.347	0.411	0.110	0.509	0.619
12	0.205	0.882	1.087	0.681	1.028	1.710
13	0.198	0.693	0.892	0.741	0.592	1.333
14	0.095	0.659	0.754	0.118	0.564	0.681
Average	**0.156**	**0.695**	**0.850**	**0.279**	**0.663**	**0.942**
Standard deviation	0.069	0.209	0.213	0.213	0.201	0.317

Table 2

RMS for control group (healthy individuals) – walking at own pace

Person	Left limb			Right limb		
	side	front	total	side	front	total
1	0.193	0.358	0.550	0.126	0.335	0.462
2	0.297	0.282	0.579	0.086	0.335	0.421
3	0.048	0.395	0.443	0.032	0.364	0.397
4	0.070	0.388	0.458	0.091	0.490	0.581
5	0.075	0.598	0.673	0.285	0.593	0.878
6	0.187	0.448	0.635	0.074	0.474	0.548
7	0.031	0.456	0.487	0.098	0.483	0.581
8	0.064	0.487	0.551	0.137	0.385	0.522
9	0.078	0.317	0.395	0.333	0.203	0.537
10	0.053	0.269	0.322	0.093	0.406	0.499
11	0.140	0.597	0.737	0.170	0.675	0.845
12	0.102	0.424	0.526	0.145	0.355	0.500
13	0.166	0.502	0.668	0.651	0.406	1.057
14	0.069	0.320	0.389	0.047	0.276	0.323
Average	**0.112**	**0.417**	**0.530**	**0.169**	**0.413**	**0.582**
Standard deviation	0.072	0.101	0.117	0.156	0.119	0.197

(brisk walking and walking at one's own pace). The results are given in Table 5.

Analyzing the results leads to the conclusion that it is not possible to determine significant differences in any of the above cases.

In the study group, in 75% of those during walking at a slow pace, and in 95% during brisk walking, we found a difference exceeding 5% between the healthy limb and the one subjected to ACL reconstruction (Table 6). However, it cannot be clearly stated that this difference is statistically significant due to the large standard deviation of the measured RMS values of resultant acceleration.

Table 3

RMS for study group (individuals subjected to reconstruction) – brisk walking

Person	Healthy limb			Limb subjected to ACL reconstruction		
	side	front	total	side	front	total
1	0.194	0.715	0.810	0.063	0.648	0.712
2	0.270	0.578	0.848	0.111	0.559	0.669
3	0.110	0.724	0.834	0.072	0.661	0.733
4	0.113	1.164	1.277	0.122	1.011	1.133
5	0.085	0.923	1.009	0.092	0.736	0.827
6	0.038	0.404	0.442	0.043	0.492	0.535
7	0.087	0.425	0.512	0.109	0.377	0.486
8	0.052	0.578	0.629	0.065	0.531	0.595
9	0.112	0.679	0.791	0.216	0.698	0.913
10	0.426	0.560	0.986	0.088	0.629	0.717
11	0.109	0.626	0.735	0.137	0.532	0.669
12	0.190	0.490	0.680	0.096	0.480	0.576
13	0.103	0.612	0.715	0.275	0.700	0.975
14	0.084	0.693	0.777	0.042	0.612	0.654
15	0.172	0.347	0.519	0.094	0.420	0.513
16	0.097	0.707	0.804	0.170	0.565	0.735
17	0.087	0.357	0.444	0.073	0.486	0.559
18	0.076	0.562	0.639	0.215	0.521	0.736
19	0.077	0.417	0.494	0.074	0.533	0.606
20	0.062	0.551	0.613	0.077	0.462	0.539
Average	**0.122**	**0.606**	**0.728**	**0.112**	**0.583**	**0.694**
Standard deviation	0.086	0.190	0.204	0.061	0.136	0.161

Table 4

RMS for study group (individuals subjected to reconstruction) – walking at own pace

Person	Healthy limb			Limb subjected to ACL reconstruction		
	side	front	total	side	front	total
1	0.068	0.564	0.632	0.043	0.505	0.548
2	0.139	0.396	0.535	0.073	0.380	0.453
3	0.071	0.482	0.553	0.035	0.420	0.455
4	0.113	1.164	1.277	0.122	1.011	0.1.133
5	0.031	0.521	0.551	0.044	0.390	0.434
6	0.021	0.280	0.300	0.019	0.355	0.373
7	0.054	0.316	0.370	0.065	0.282	0.348
8	0.035	0.400	0.435	0.048	0.379	0.427
9	0.077	0.370	0.447	0.085	0.475	0.560
10	0.384	0.334	0.718	0.041	0.429	0.470
11	0.058	0.328	0.385	0.097	0.290	0.387
12	0.099	0.340	0.439	0.060	0.323	0.383
13	0.162	0.501	0.662	0.148	0.352	0.500
14	0.067	0.293	0.360	0.033	0.368	0.401
15	0.142	0.275	0.417	0.067	0.339	0.406
16	0.038	0.402	0.440	0.074	0.336	0.410
17	0.034	0.440	0.474	0.072	0.413	0.484
18	0.027	0.268	295	0.143	0.267	0.410
19	0.054	0.282	0.336	0.038	0.372	0.410
20	0.039	0.225	0.264	0.045	0.225	0.269
Average	**0.086**	**0.409**	**0.495**	**0.068**	**0.395**	**0.463**
Standard deviation	0.079	0.196	0.217	0.035	0.156	0.167

Table 5

Collective results of bilateral Student's t-test statistics and their corresponding borederline values of *p*. confidence level. Calculations for the acceleration signals: ax, (side), az (front) and aw (total)

	Healthy – brisk		Healthy – own pace		After reconstruction – brisk		After reconstruction – own pace	
	t	*p*	*t*	*p*	*t*	*p*	*t*	*p*
side	1.98	0.0582	1.2	0.242	0.413	0.682	0.908	0.37
front	0.398	0.693	0.092	0.927	0.43	0.67	0.244	0.809
total	0.869	0.393	0.818	0.42	0.57	0.572	0.509	0.613

Table 6

Size evaluation according to the criterion of the relative RMS difference between limbs for people undergoing ACL reconstruction

	Difference up to 5%		Difference above 5%	
	n	%	n	%
Brisk	1	5%	19	95%
Slow	5	25%	15	75%

DISCUSSION

In practice, there are many methods of gait analysis used in clinical medicine and sports. Accelerometric analysis is being more frequently mentioned as one of the main methods of movement analysis, among others, by Levine[5]. In the research by Golec et al.[6], we used the CQMotion Elektronik System, MEMS type with inertial MEMS sensors to evaluate movement in young people. The study involved 36 healthy people aged 20 to 23 years. The sensors were placed on the rear upper iliac spines. We measured the time of the gait cycle, RMS and the impact of lateralization at the time of loading the lower limb. Statistical analysis of the results was based on non-parametric tests, in contrast to the present study where the results were developed using a test for significance of differences between two means. The test results indicated that during gait, asymmetry of movement trajectory was observed in both legs in the frontal plane and its absence in the sagittal plane, and the RMS value of gait had impact on its symmetry. However, in the presented results of the study, we analyzed the impact of walking speed on the RMS value.

In the research by Staab et al.[7], the authors used sensors including an accelerometer and a 3-D gyroscope, located on the trunk and limbs, as well as the Vicon 460 optoelectronic system for gait analysis. The study included 12 patients with osteoarthritis of the knee joint and 7 healthy individuals. The results of both systems were correlated. The results obtained using the gyroscopic and accelometrical sensors allowed to demonstrate the differences in pathological and normal gait. The authors emphasize the reliability and accuracy of the method, which can be used both for movement analysis in clinical medicine as well as in sports.

In the work by Golec et al.[8], using the presented gait analyzer in the study, symmetry of gait disorders in people suffering from chronic back pain is described. The study comprised of a total of 53 people (study and control group). The study group consisted of 25 people with chronic back pain at different levels, including 18 women (72%) and 7 men (28%). The control group consisted of 28 healthy people, including 19 women (68%) and 9 men (32%). The symmetry of the alternating movement of the limbs during gait was assessed. The sensors were placed on the appendix of the left (L) and right (R) shoulder blade, and the L and R tibial tuberosity. The duration of the gait cycle for both limbs while walking at one's own pace and during brisk walking was also examined. The results allowed to observe significantly higher gait disturbances in both groups during brisk walking. In our study, we also analyzed gait during brisk walking and at one's own pace, however, focusing on answering the question: does the gait speed have impact on the change in acceleration value measured at the tuberosity of the limb treated using ACL reconstruction compared to the healthy limb? Research showed that the pace of gait has impact on the value of RMS acceleration in both the study and the control group.

Accelerometric gait analysis has also been used in patients with damage to the central nervous system. The work by Goldfinch et al.[9] presents the results of analyzing changes in acceleration at different levels of motor organs in patients after ischemic stroke and healthy people. The study group consisted of 23 people, including 11 healthy subjects at the average age of 20 years, and 12 people at the average age of 69 who had experienced ischemic stroke. Measurements were made using an accelerometer gait analyzer. Sensors were attached to the lateral bone of the L and R shin, at the height of the knee joint gap, the greater trochanter of the L and R femur, the spinous processes of the L3 and C7 vertebrae and to the top of the head. Research showed a reduction tendency in the acceleration amplitude at increasingly higher levels of the motor organ in both groups.

Elaboration of the results was conducted using the methodology of the above-mentioned works.

Analyzing the timing of the accelerations (Table 3 and 4), it was found that the acceleration courses in the lateral direction are characterized by significantly smaller amplitude than the accelerations in the front-back direction.

In the tested samples, standard deviation was high, which was most likely caused by the manner of conducting the experiments. The sample regarded a distance of only 4 × 8 meters each, forced by the length of the cables connected to the sensors. The short distance forced subjects to perform changes in direction, which could have also distorted the gait image.

Analyzing the obtained results (Table 1-4), it can be concluded that the standard deviation of the differences in the lateral direction are relatively large. This is particularly evident during walking at one's own pace (Table 4), wherein the standard deviation is almost equal to the average value. As a result, acceleration measurements in this direction are unreliable. This may be due to the fact that the values of lateral accelerations are small and therefore, error has a higher relative proportion in the measurement. The level of significance 0.05 (*p* value in the Student's t-test) adopted in this paper does not allow to unambiguously answer the question: do the differences in accelerations between the left and right limb for the control group and patients after ACL reconstruction differ from one another?

Despite the fact that there was a difference of over 5% between the healthy limb and the one subjected to ACL reconstruction for 75% during slow walking, and 95% during brisk walking, it cannot be clearly stated that this difference is statistically significant because of the high standard deviation of the measured RMS total acceleration values.

Analyzing the standard deviation of the results, large values can be observed. It would be achievable to improve the measurements (decreasing standard deviation) if it were possible to carry out registration of acceleration records over a longer period of time. But this is not feasible because the current measurements are limited by cable length. One hypothesis requiring examination in the future assumes that over a longer time frame, steps become stabilized. In the case of this work, the distance was only 8 m, i.e., subjects walked about 10 steps.

CONCLUSIONS

1. The measured average acceleration values obtained for the tibial tuberosity of the healthy limb in the forward direction and the acceleration values for the limb with a history of ACL reconstruction are similar.
2. The walking speed has influence on the acceleration value observed in the RMS values in both the study and control group. During gait at one's own preferred pace, the mean values for all the enrolled participants were lower.
3. Large asymmetry was not observed between the limbs on the basis of the RMS value in the study or control group.

Conflict of interest: none

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Address for correspondence
Dr hab. Joanna Golec
Akademia Wychowania Fizycznego im. Bronisława Czecha w Krakowie
Wydział Rehabilitacji Ruchowej
Katedra Rehabilitacji Klinicznej
Zakład Rehabilitacji w Traumatologii
Al. Jana Pawła II 78, 31-571 Kraków, Poland
e-mail: joannagolec@wp.pl